High repetition sample strategy for the HED instrument at European XFEL

TARG2 Workshop

20/04/2015

Paris, France

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A. Schmidt, U. Zastrau & Th. Tschentscher

Content

- European XFEL
- Science case
- Instrument design overview
- High repetition sample strategy

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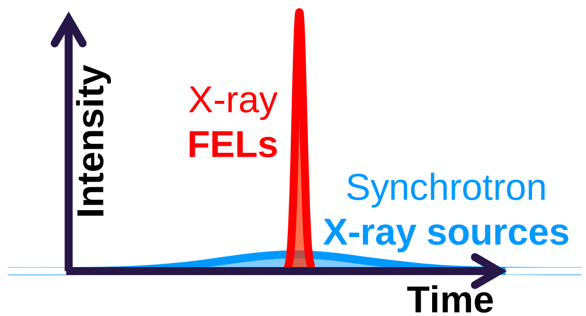
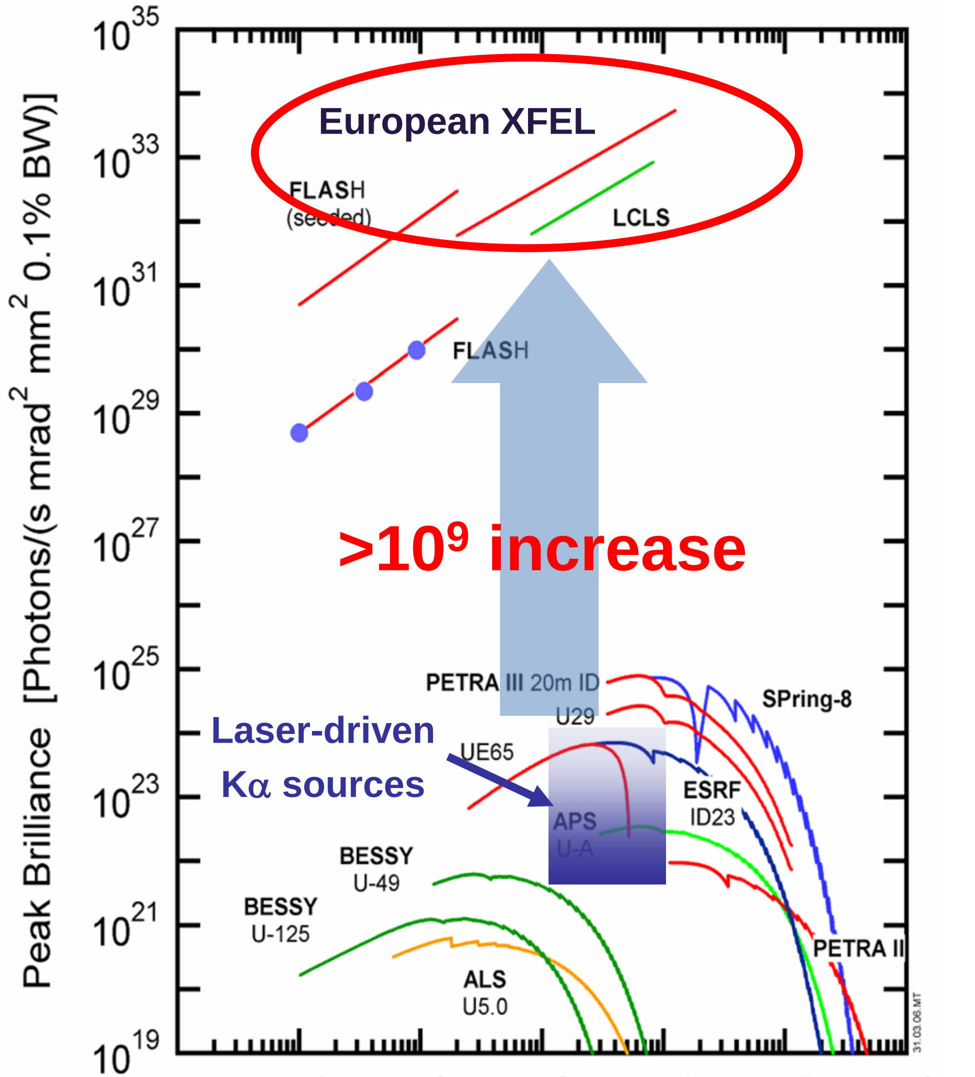
HED study requires short and intense x-rays. → X-ray free electron laser

XFEL properties (HED at XFEL.eu)

- Fully tunable between 3 – 25 keV
- Short pulse duration: 2 – 100 fs
  - → 10^3-10^4 × shorter than conventional sources

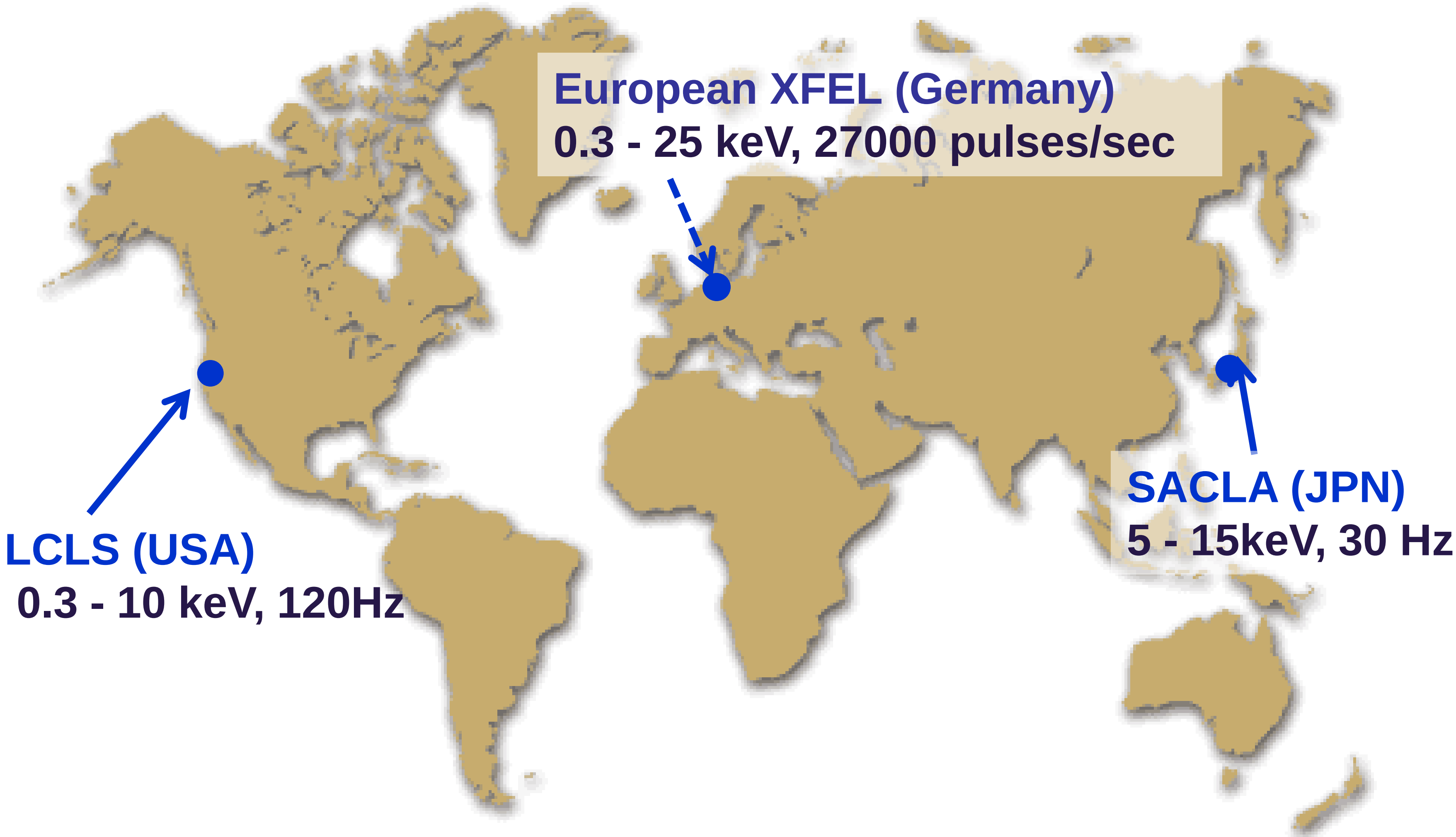


- High # of photons: 10^{11}–10^{13}/pulse
- Highly monochromatic: $\Delta E/E \sim 10^{-3}$
- High repetition: 27000 /sec
- Full transverse coherence

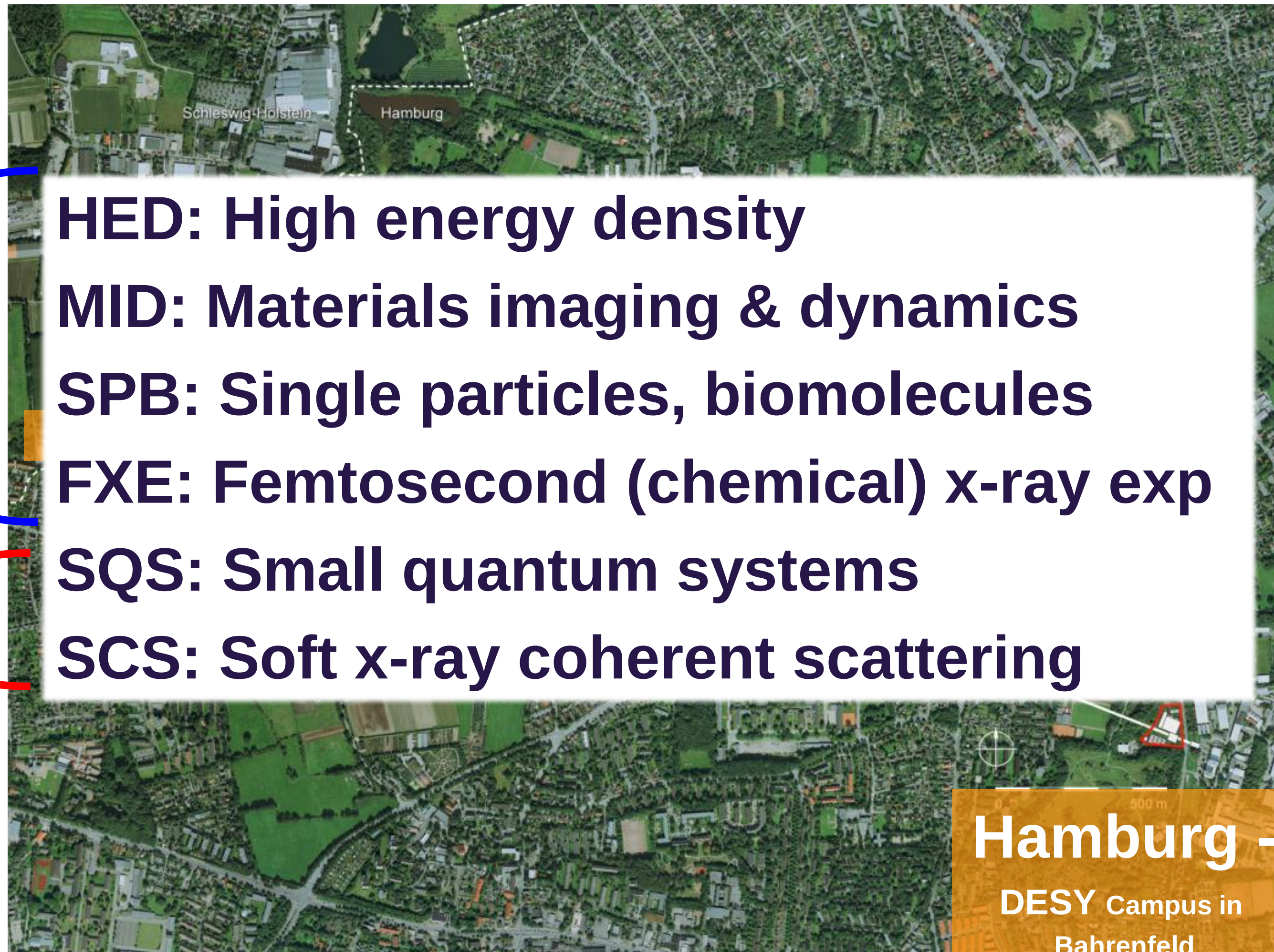


Tremendous possibilities for HED studies

Hard X-ray FELs worldwide



European XFEL
User facility for multi-disciplinary science



Hard X-ray
3 - > 20 keV

- HED: High energy density
- MID: Materials imaging & dynamics
- SPB: Single particles, biomolecules
- FXE: Femtosecond (chemical) x-ray exp

Soft X-ray
0.26 - 3 keV

- SQS: Small quantum systems
- SCS: Soft x-ray coherent scattering

Hamburg - DESY Campus in Bahrenfeld

European XFEL
User facility for multi-disciplinary science

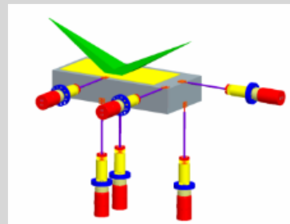
Schenefeld

~ 3 km

DESY Campus in Bahrenfeld

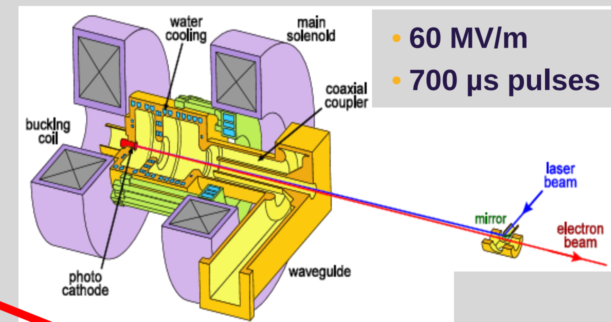
6 Scientific instruments

~1 km of X-ray beam transport



- 3 systems
- 1.2 km
- 1m mirrors

Low emittance electron injector



- 60 MV/m
- 700 µs pulses

3 Undulators

- >200 m

2km Superconducting e- accelerator

- 23 MV/m
- 800 cavities
- Up to 17.5 GeV

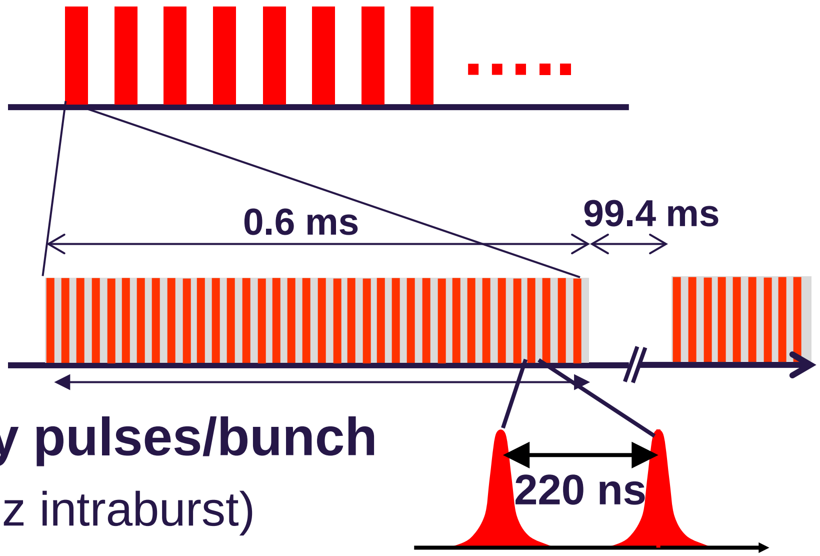
Project cost:	1147 B€
First beam:	end 2016
User op's:	2017

Time plan

1st X-ray FEL beam	**April 2017**
1st user operation	**end 2017**
Full operation	**Mid 2018**

Max 4.5 MHz intraburst x-ray delivery

10 Hz burst



Full pulse train (27000 pl/s)

Max 2700 x-ray pulses/bunch

(4.5 MHz intraburst)

Single pulses (0 – 10 pl/s)

1 x-ray pulse per train **= 10Hz**

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High Energy Density matter occurs widely

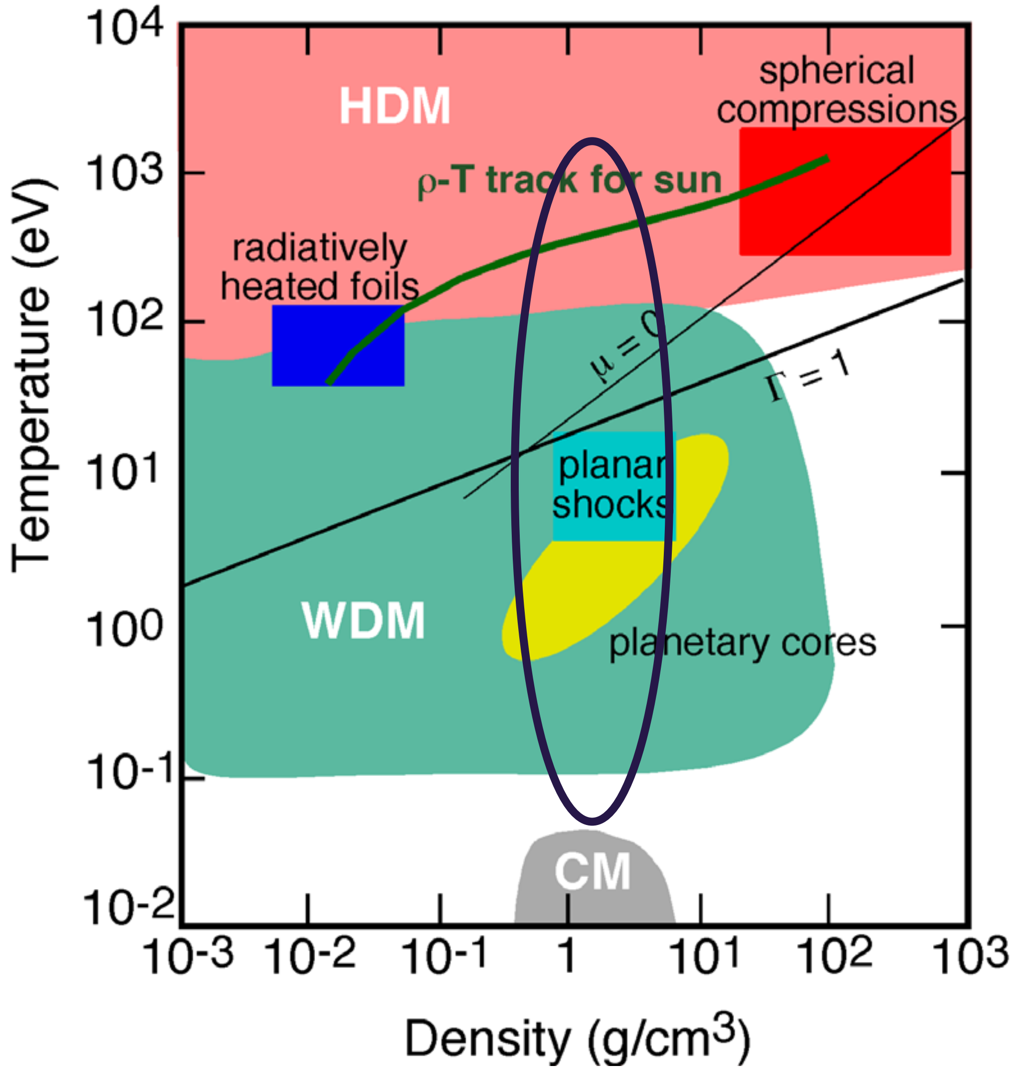
Hot Dense Matter (HDM) occurs in:

- Supernova, stellar interiors, accretion disks
- Plasma devices: laser-produced plasmas, Z-pinches
- Directly and indirectly driven inertial fusion experiments

Warm Dense Matter (WDM) occurs in:

- Cores of planets
- Systems that start solid and end as a plasma
- X-ray driven inertial fusion experiments

Hydrogen phase diagram



HED study requires short and intense x-rays

Probe HED states:

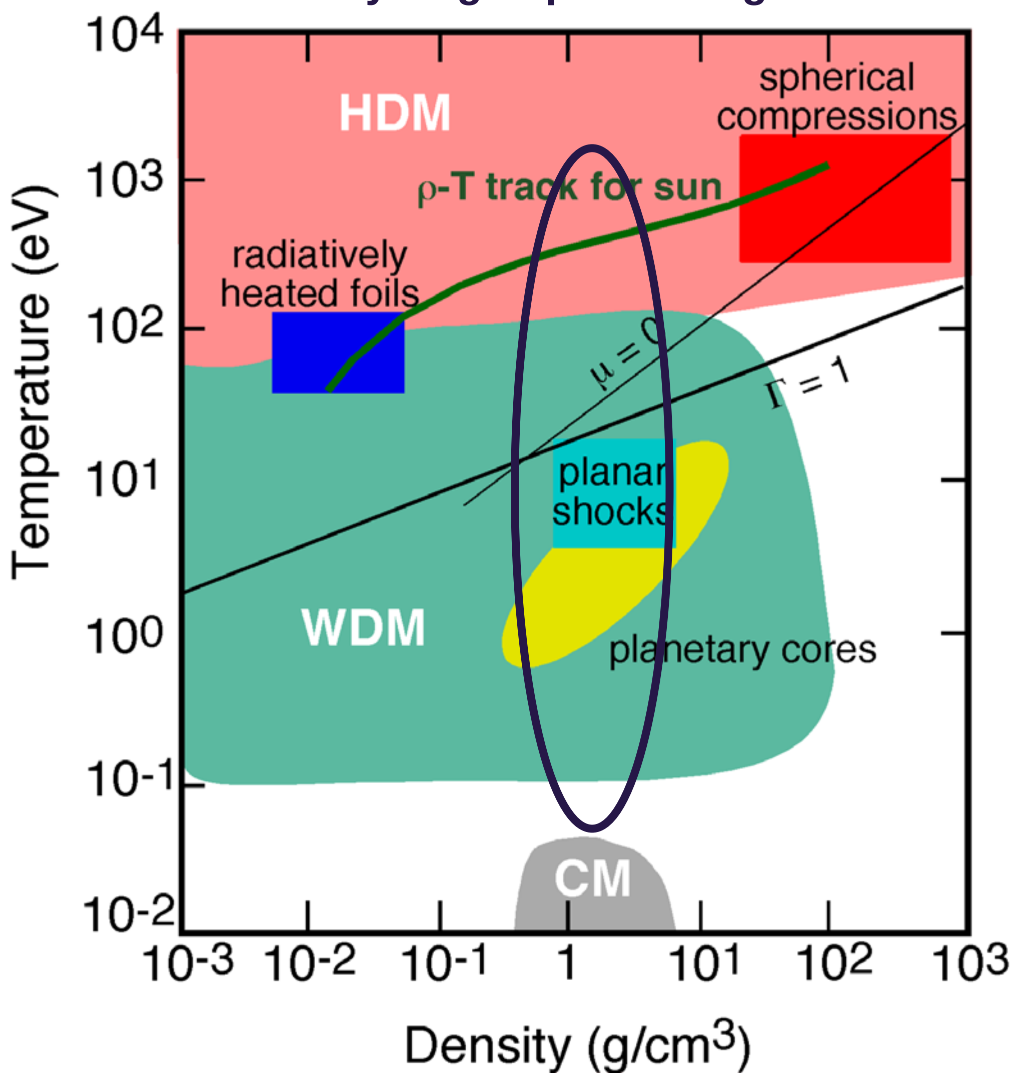
- **Intense x-ray** - to probe dense matter at finite temperature
- **Ultrashort pulses** - to study highly transient behavior and remove hydrodynamic changes

Creating HED states:

➔ **Optical lasers, or, XFEL**

- Volumetric heating
- Short duration (≤100 fs)
- High # of photons per pulse
- Fully tunable

Hydrogen phase diagram



European XFEL

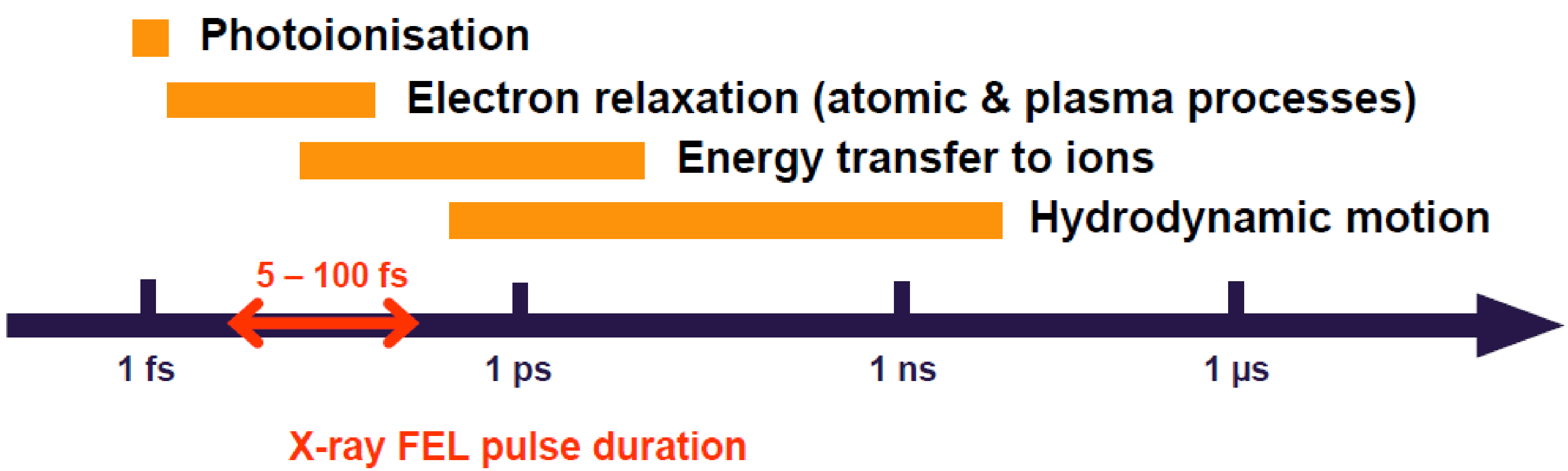
Probing time scales

X-ray probe

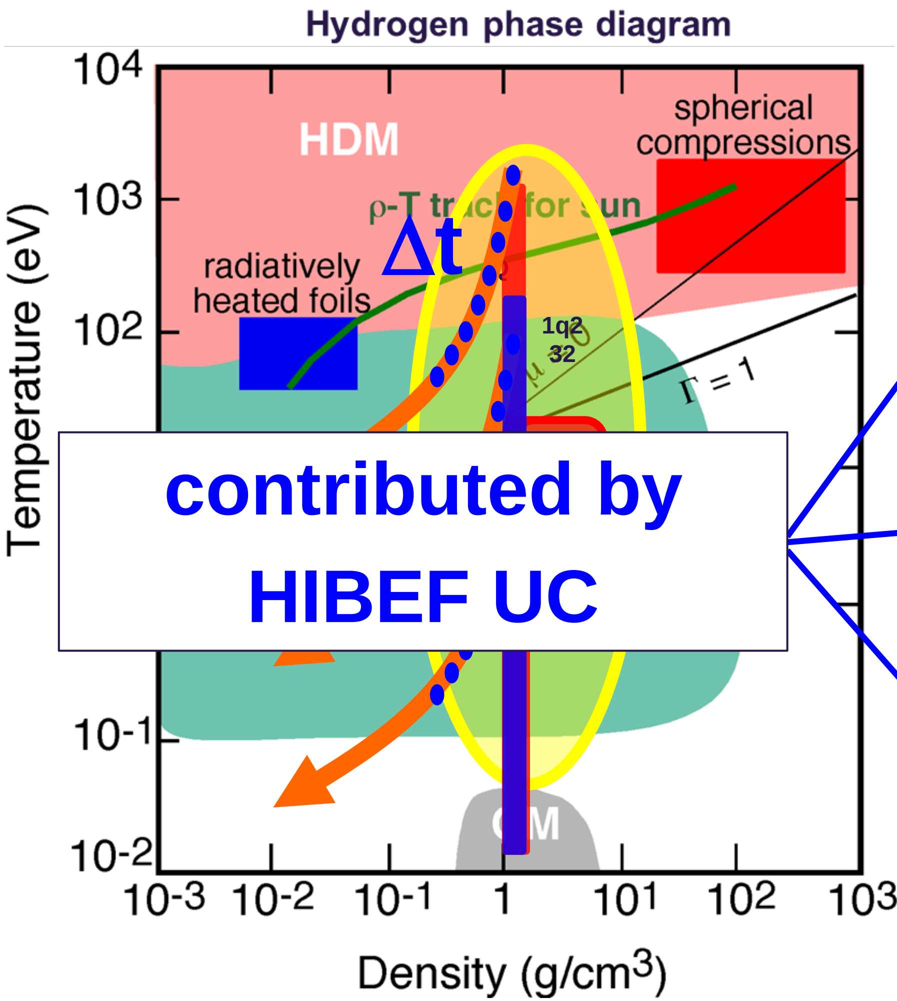
- Bragg diffraction
- Elastic, inelastic scattering
- Emission spectroscopy
- Absorption spectroscopy
- X-ray (coherent) imaging

X-ray FEL is an instantaneous probe

- XFEL duration : 1 – 100 fs
- Shorter than electron-ion equilibration time scale in solids ($T_e \neq T_i$)



Three high-power optical lasers



3 optical lasers

- Pump-probe (PP) $>10^{17}$ Wcm^2
  - ➔ 0.2-3mJ, 0.2-4.5 MHz, 15 fs
  - ➔ 4-100mJ, 0.2-4.5 MHz, 800 fs
- Ultra-high intensity (UHI) 100TW
  - ➔ 3J, 30fs, 10 Hz on sample
- High energy (HE)
  - ➔ 100J, 2–15ns, 1-10Hz, ramped
  - ➔ UK contribution to UC

Pulsed magnet

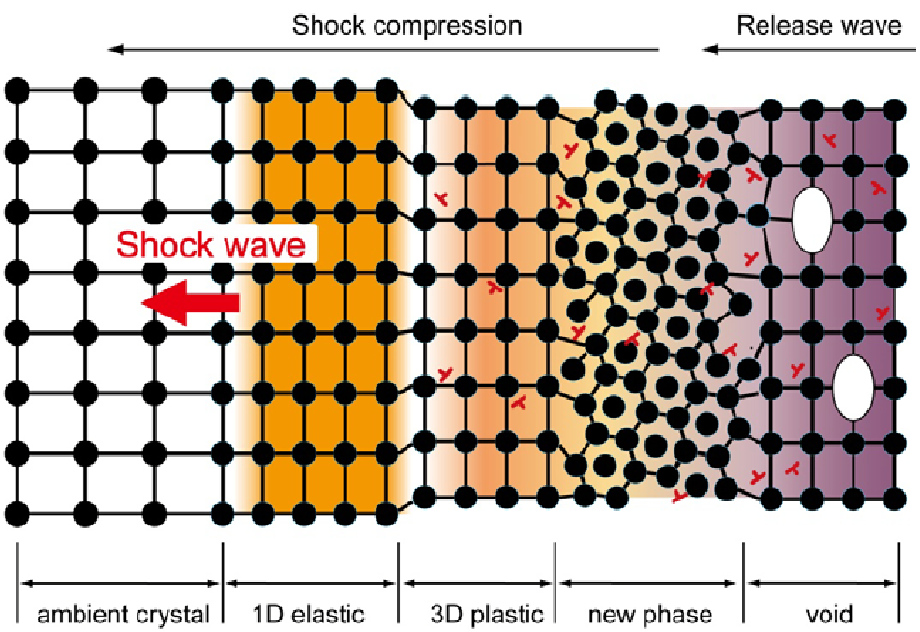
- ~50 Tesla (10 kbar, 1Gpa)

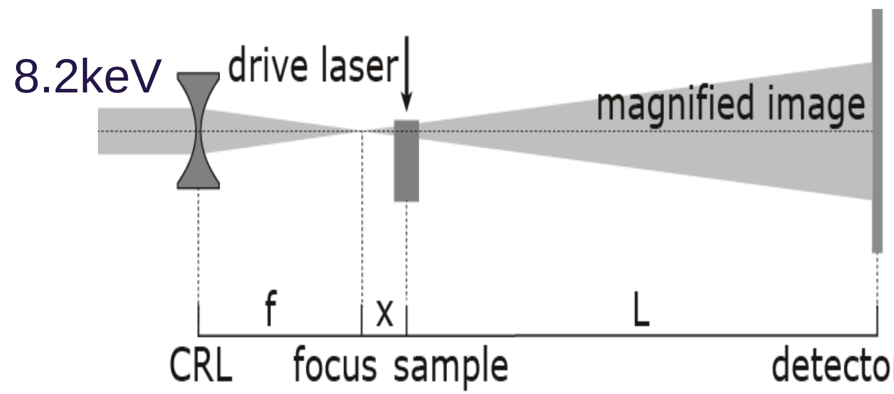
XFEL

- $>10^{11}$ phot, $<\mu m$, $> 10^{19}$ W/cm^2

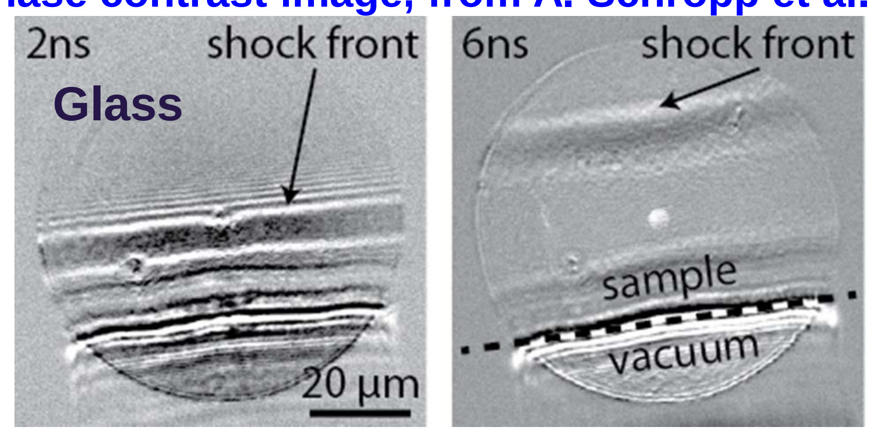
Dynamic shock compression by ns laser

Extend static compression techniques (e.g. DAC: P > 100-400 GPa; T ~1000-4000 K)





Phase contrast image, from A. Schropp et al.

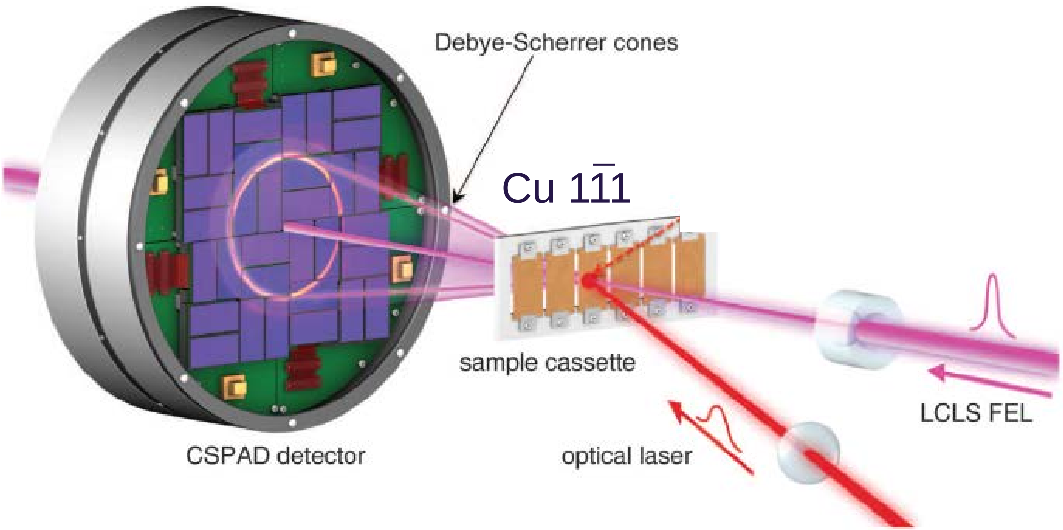


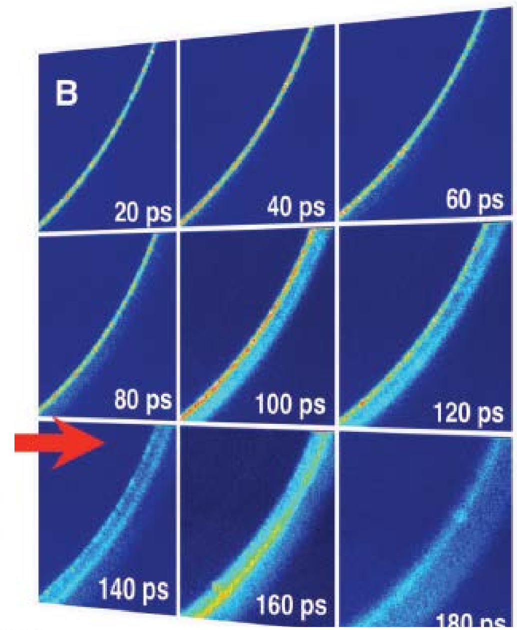
Accessible parameters

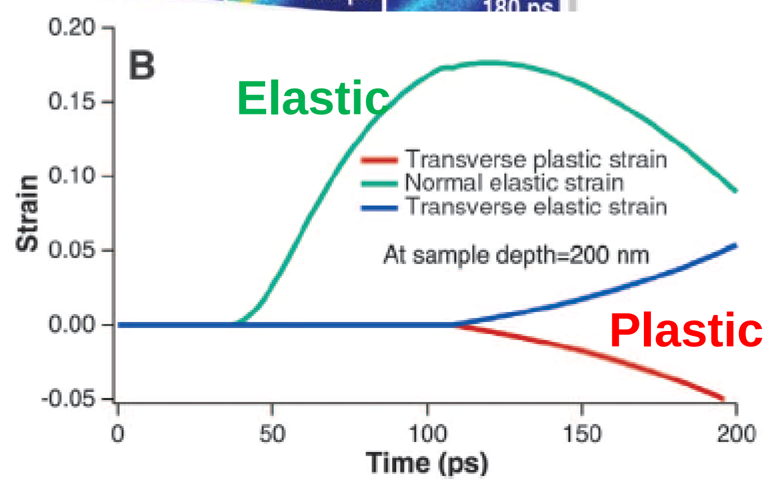
→ Shock velocity, density change, deformation length & time scale, viscosity

TECHNISCHE UNIVERSITÄT DRESDEN VolkswagenStiftung SLAC NATIONAL ACCELERATOR LABORATORY LCLS

X-ray diffraction of laser-shocked copper





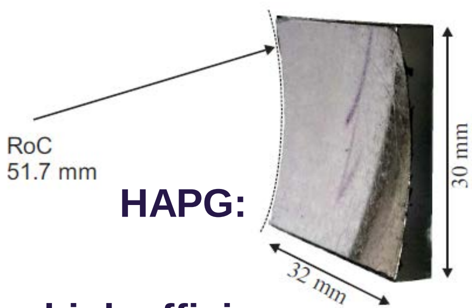


Accessible parameters

- Phase transitions
- Melting
- Stress, strain

D. Milathianaki et al., Science 342, 220 (2013)

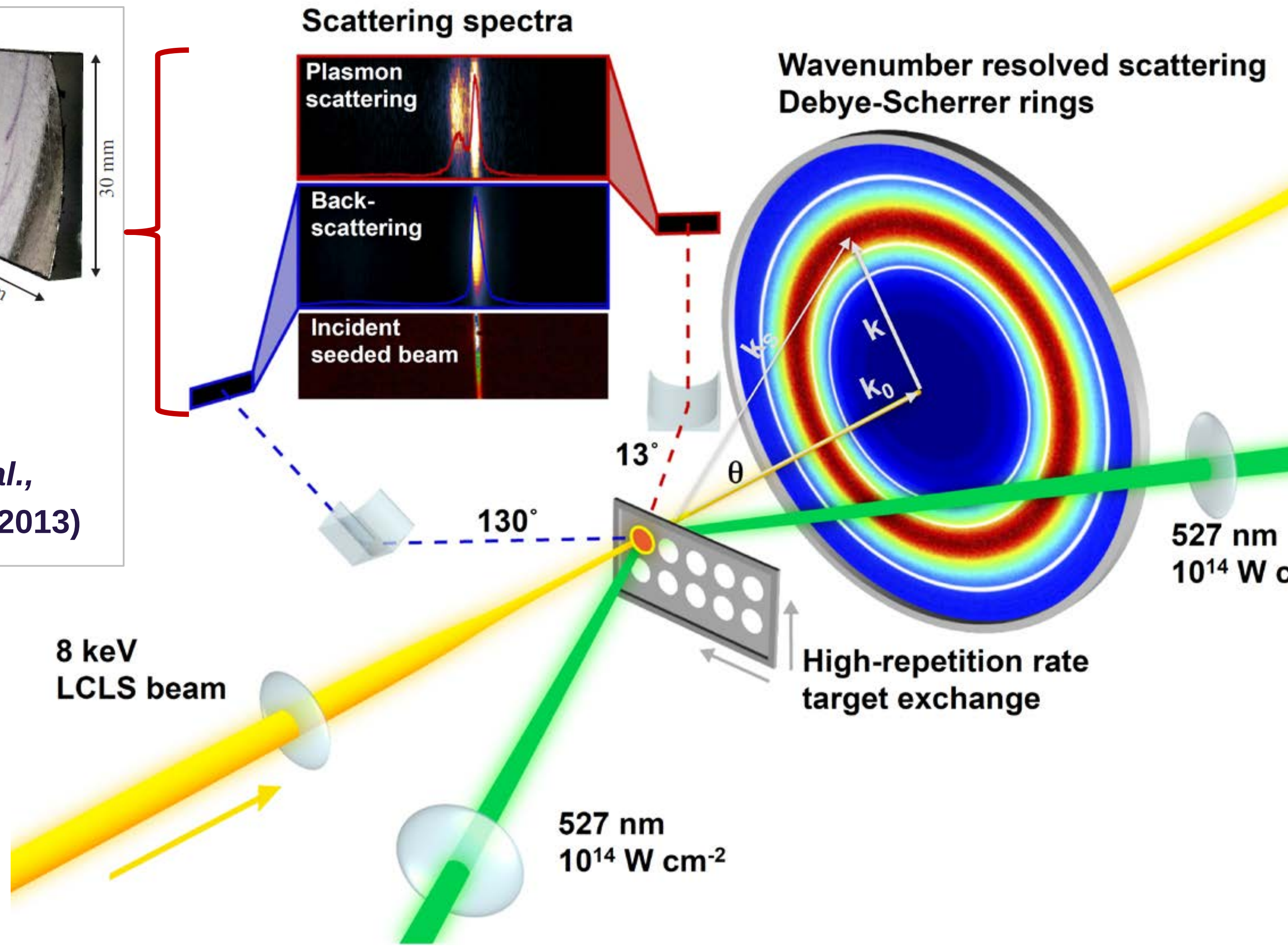
Counterpropagating Shocks in Al



HAPG:

high efficiency
low aberrations
9 eV resolution

U. Zastrau *et al.*,
***JINST* 8 P10006 (2013)**



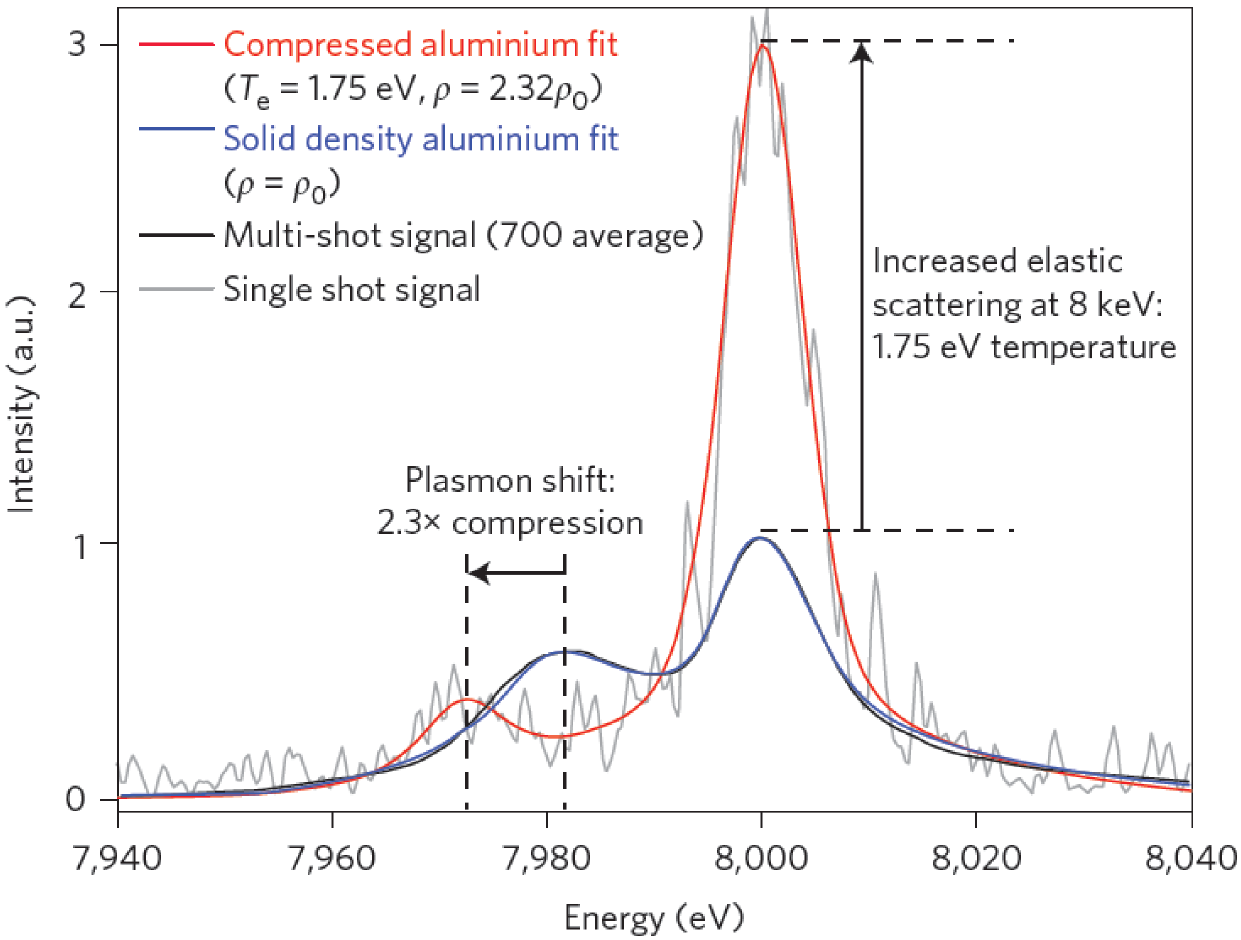
J. B. Fletcher et al., Nat. Phot. 9, 274–279 (2015).

Courtesy U. Zastrau

Shifted plasmon at compression

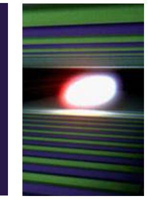
Plasmon shift via Gross-Bohm dispersion relation, where the plasma frequency dominates and yields the density increase:

$$\omega(k) \sim \omega_p = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}}$$



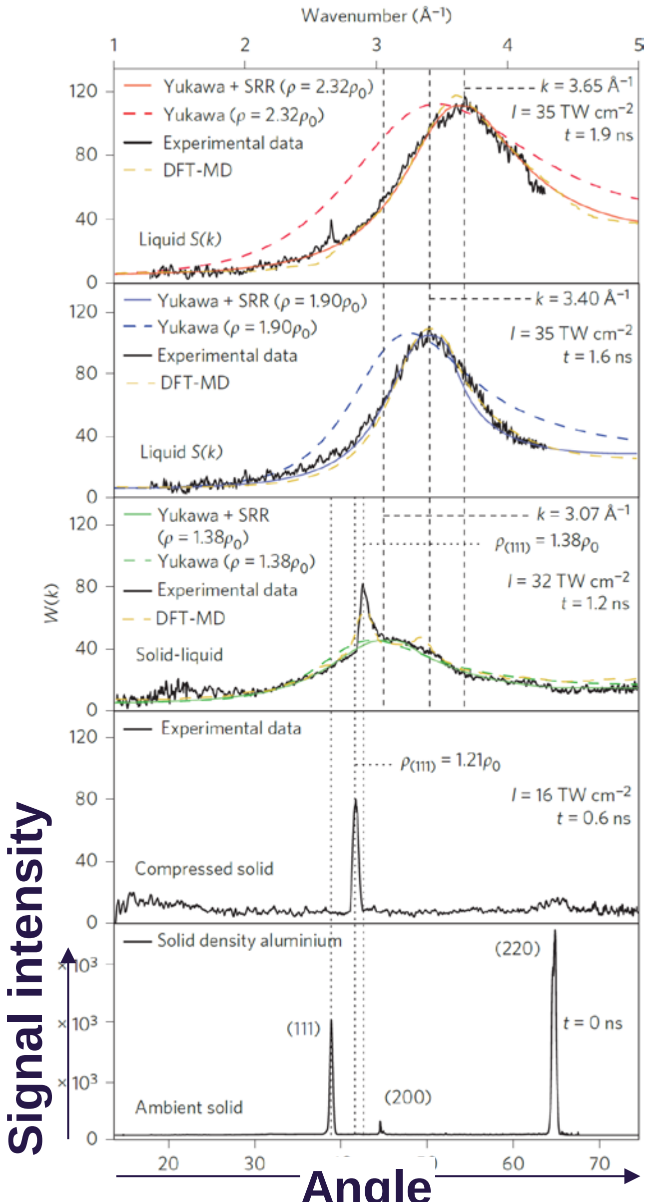
J. B. Fletcher et al., Nat. Phot. 9, 274–279 (2015).

Courtesy U. Zastrau



S(*k*) during compression

Courtesy U. Zastrau



The angle for peak scattering increases further to 56° when higher densities are reached after coalescence.

At higher shock strength and compression, aluminum melts, Bragg peaks disappear, and a broad ion-ion correlation peak at 50° is observed.

First appearance of a broad ion-ion correlation peak is observed together with a Bragg peak shifted further to larger scattering angles.

Data from compressed solid aluminum show a shift of the (111) Bragg peak by 3° and compression of $1.13\rho_0$.

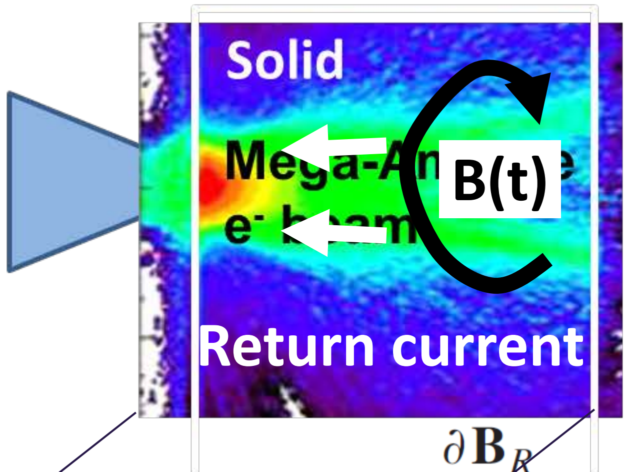
Bragg peaks from Debye-Scherrer rings are shown at t=0 ns. The peaks at 38°, 45°, and 65° correspond to (111), (200), and (220), respectively.

J. B. Fletcher et al., Nat. Phot. 9, 274–279 (2015).

Relativistic laser matter interaction

Generation | **Transport** | **Secondary sources**

Ultra-high intensity (UHI) laser
$> 10^{18}$ Wcm^{-2}
Short pulse τ_L<ps

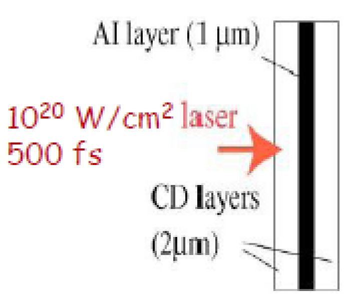


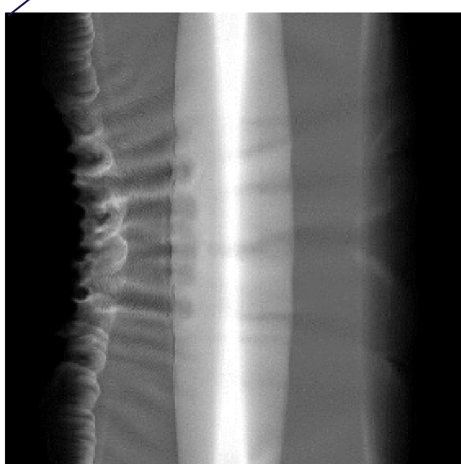
→ Ions
Positrons
→ Neutrons
→ X-rays

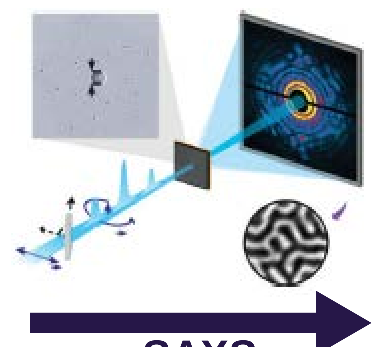
High quality
- Bright
- Short (fs – ps)
- Energetic (keV-MeV)

$$\frac{\partial \mathbf{B}_R}{\partial t} = -(\eta\nabla\times\mathbf{J} + \nabla\eta\times\mathbf{J})$$ ➔ **MG - GG**

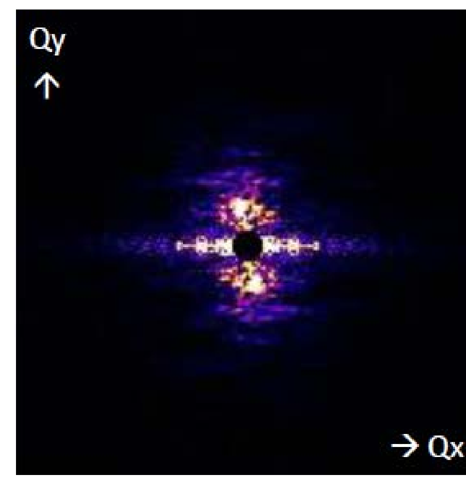
Buried layers
(Courtesy: T. Cowan, T. Kluge)







SAXS
(Simulation: C. Gutt)



T. Kluge et al., Phys. Plasmas 21, 033110 (2014).

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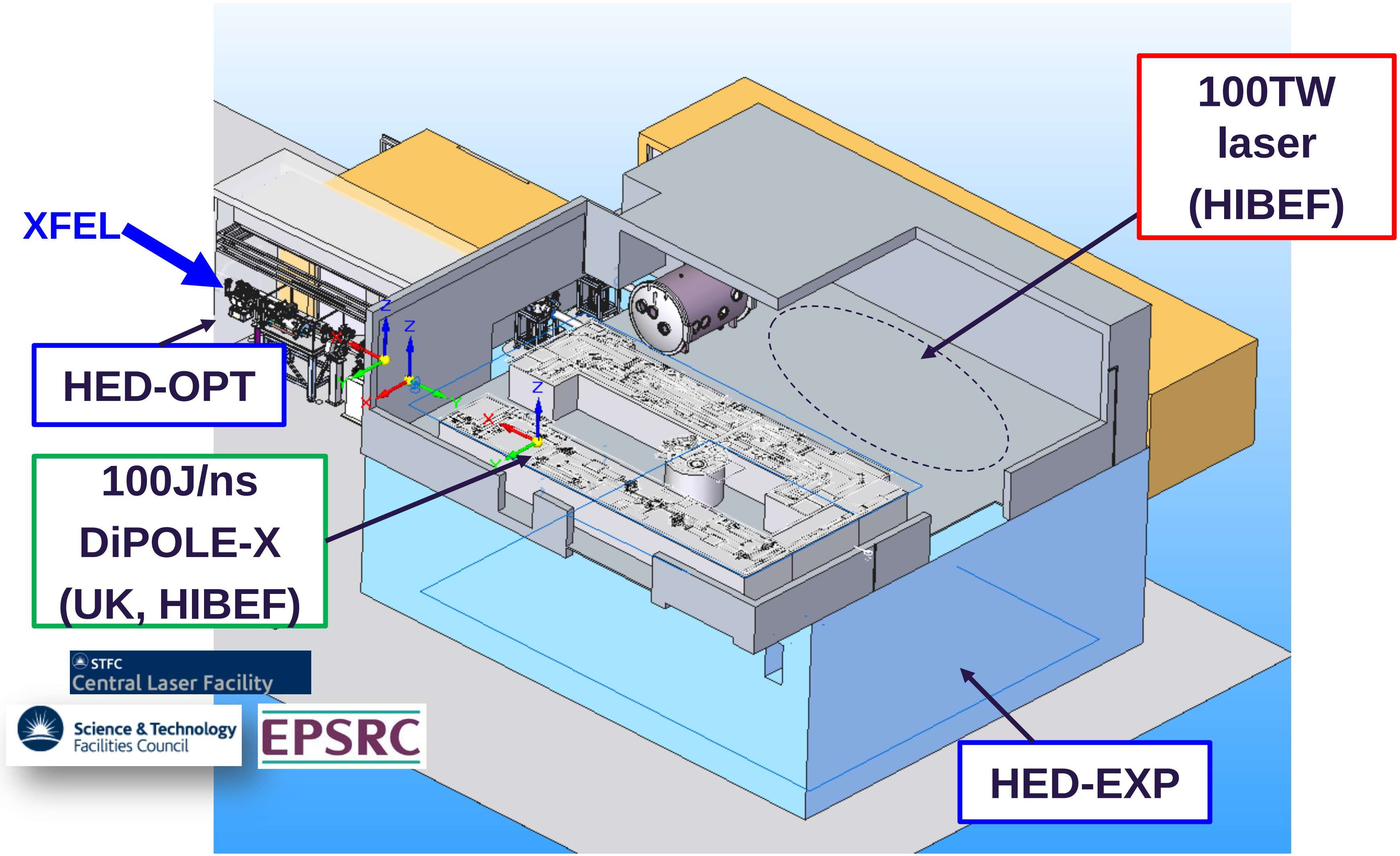
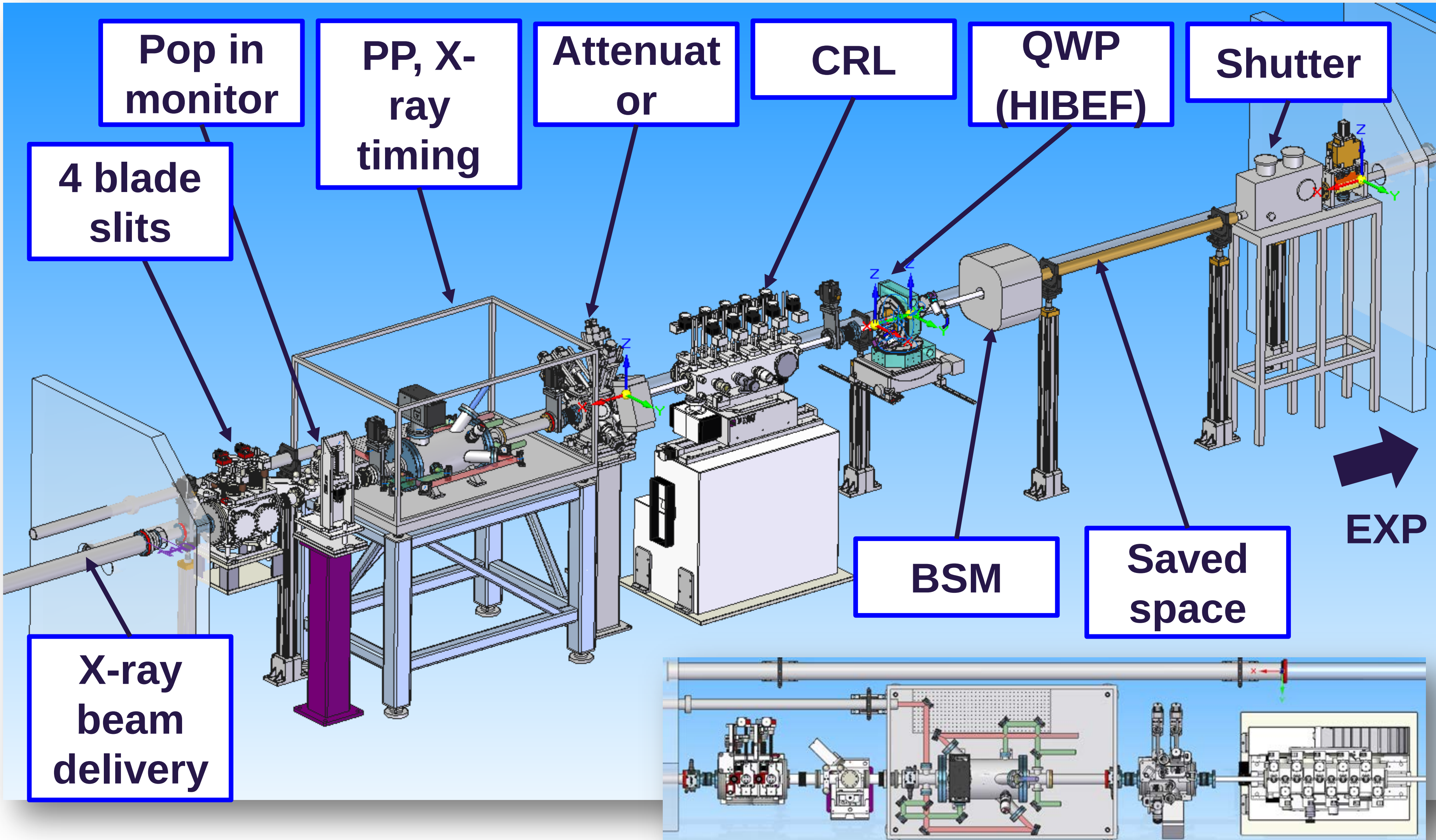
High power laser installation (elevated level)

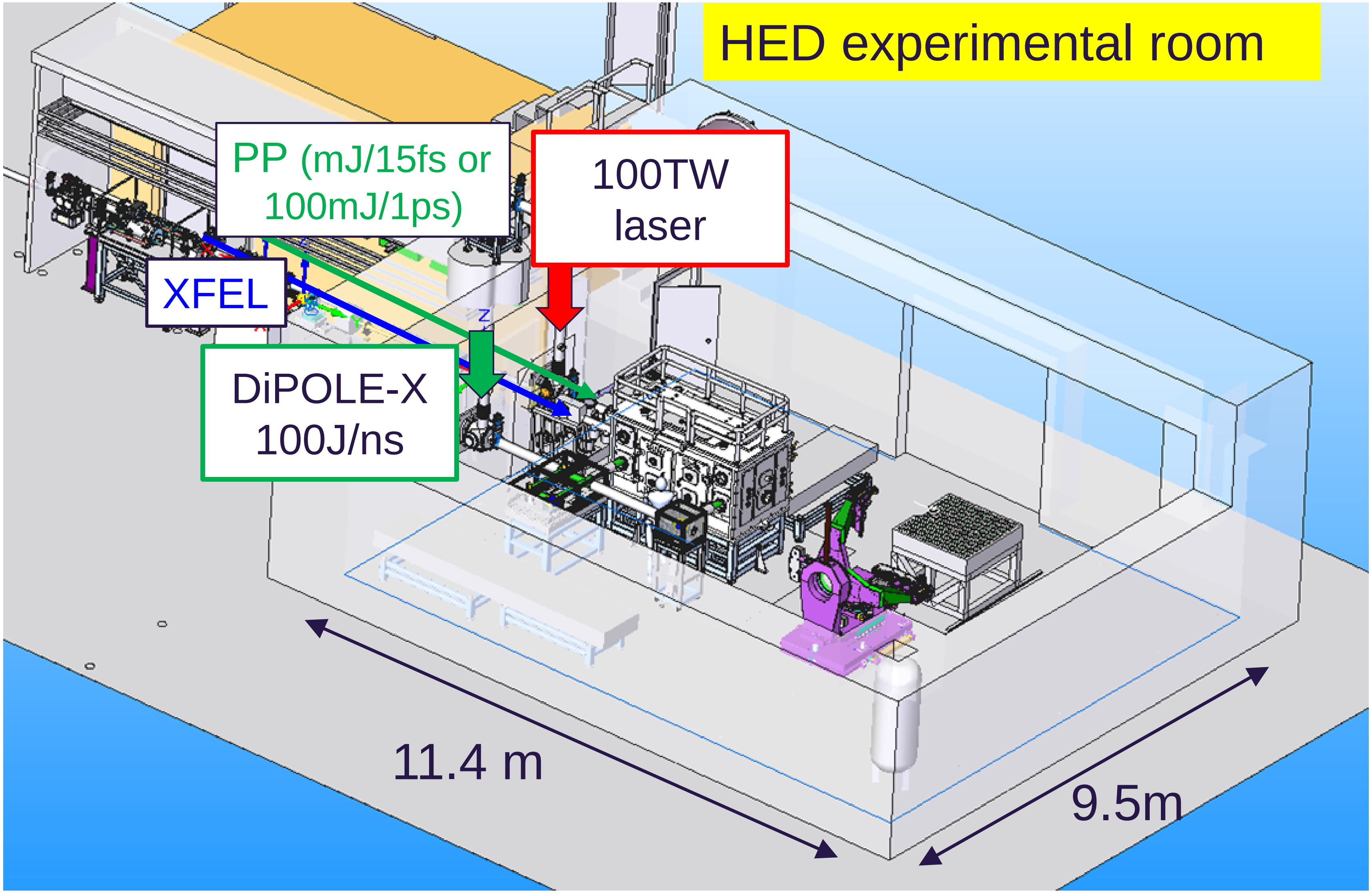


X-ray optics hutch (HED-OPT)



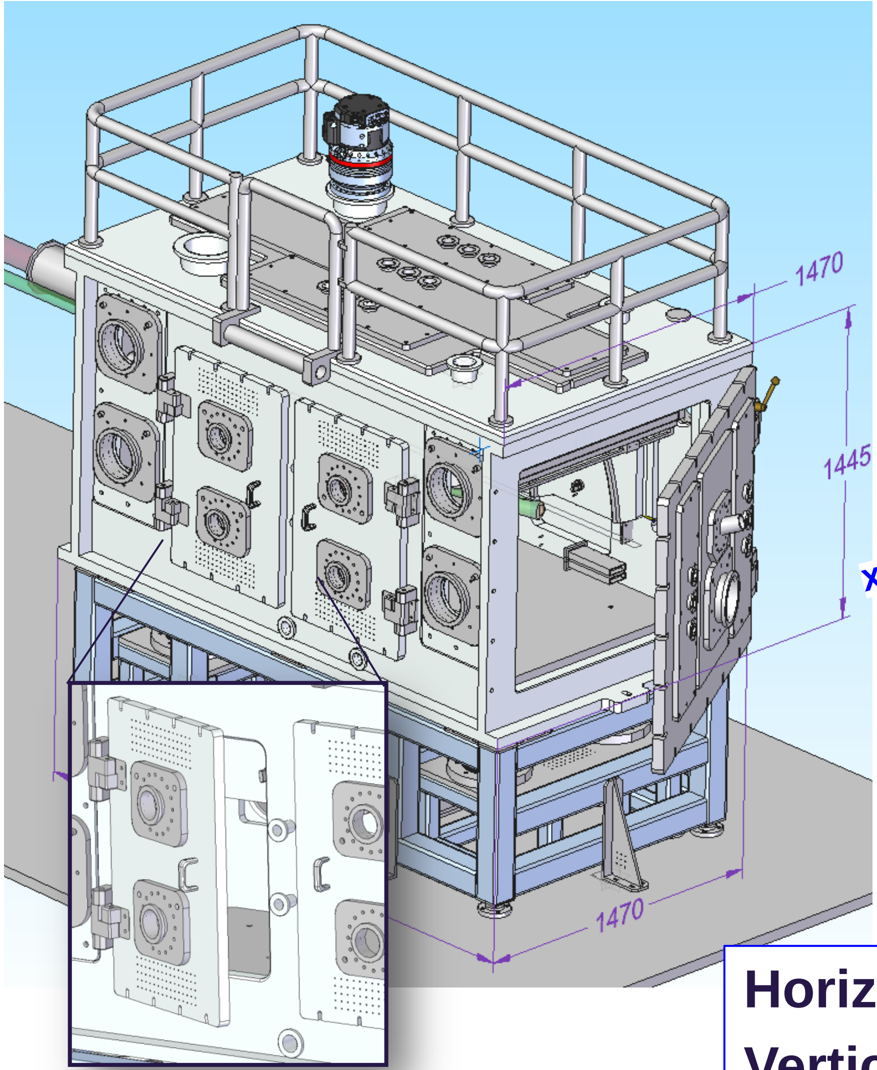
HED, European XFEL,
motoaki.nakatsutsumi@xfel.eu

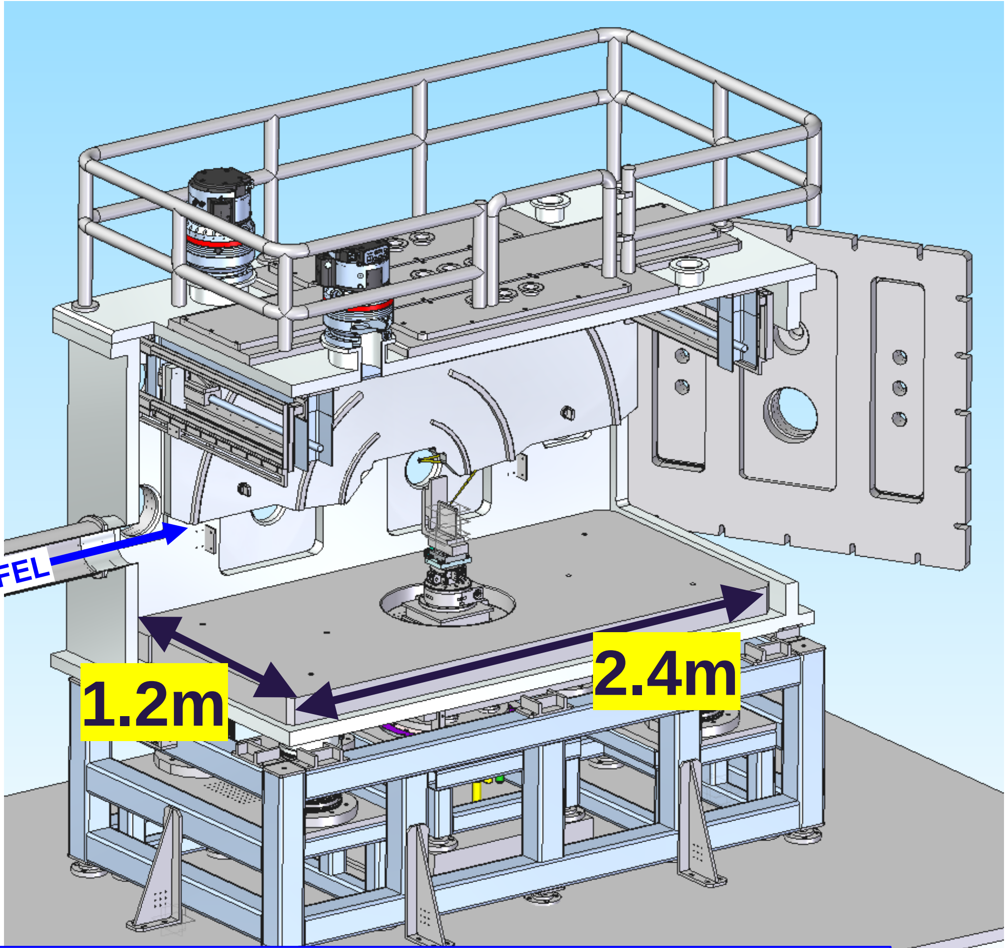
Experimental hutch and beam transports



motoaki.nakatsutsumi@xfel.eu

Large vacuum interaction chamber to accommodate versatile setups





Horizontal plane: optical laser transport

Vertical plane: x-ray diagnostics

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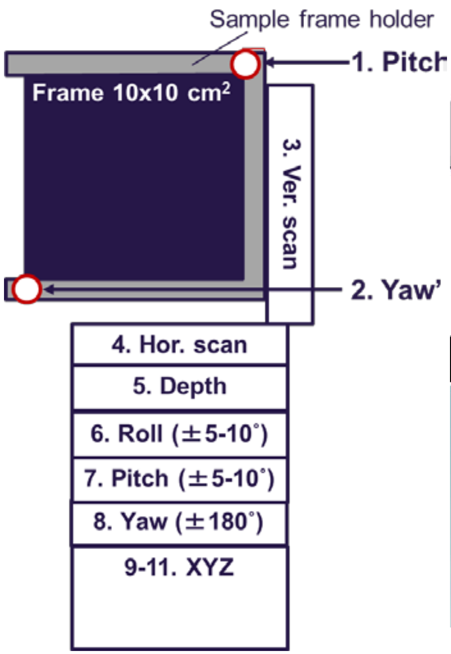
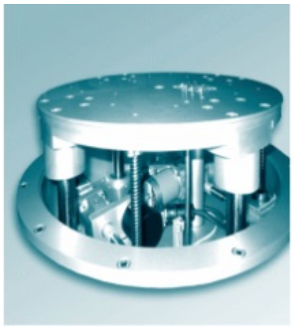
General concept/strategy: Provide capability of 10 Hz sample scan.

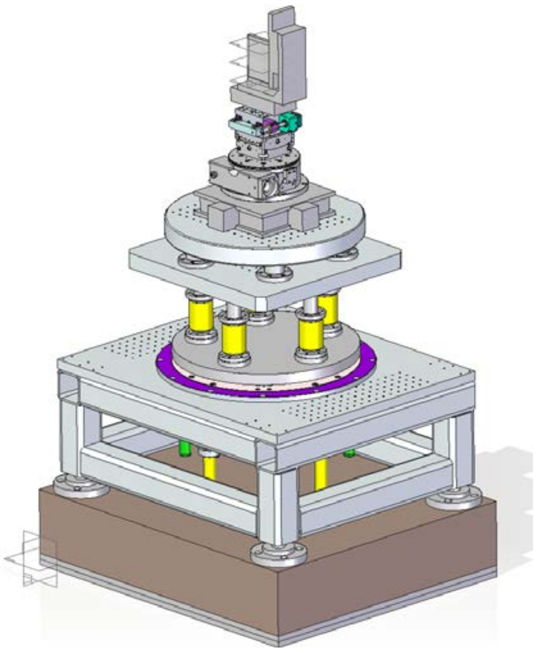
- **‘high repetition’ is an unique capability of the European XFEL**
  - X-ray and PP-laser: >MHz (intraburst)
  - High power lasers (100J/ns, 3J/30fs): 10Hz
    - **Target refreshment ➔ ‘at least’ 10Hz (capability)**
- **Target type: solids**
- **Time scale: working system by end 2016**
- **Method:**
  - Many samples on frame, scan at 10hz, change the frame without breaking chamber vacuum – day-1 system
  - Other (more ambitious) methods – continue to seek

10 Hz-sample scanner

- 10 x 10 cm^2 frame
- 10Hz sample scan with micro-metre precision
- Map the surface of the sample membrane: microscope outside
- Recording the actual position of each sample
- Storing the data to provide a position compensation motion during 10Hz scanning

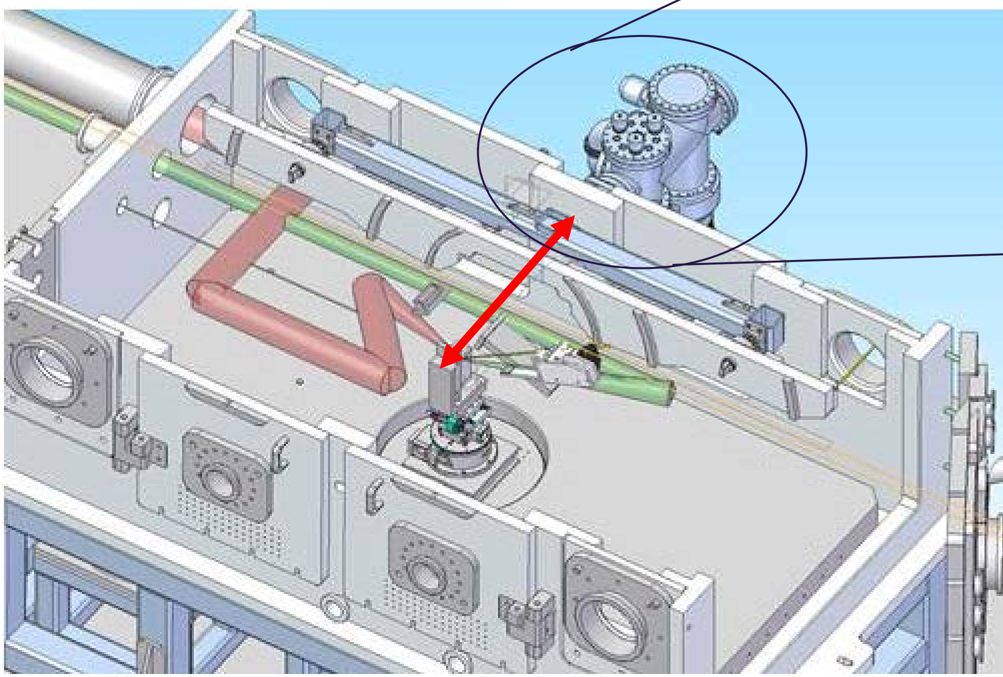


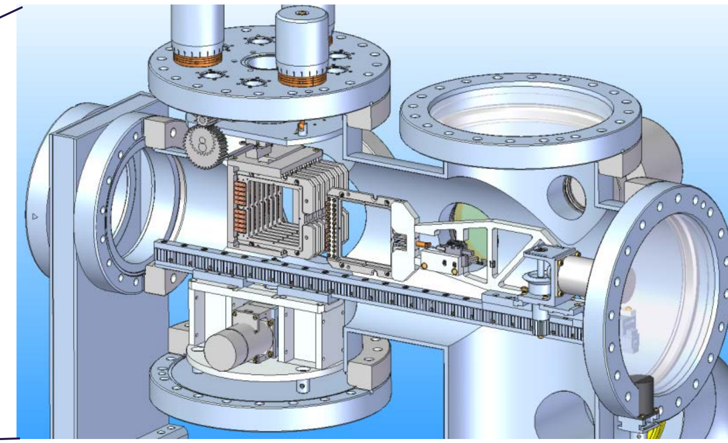


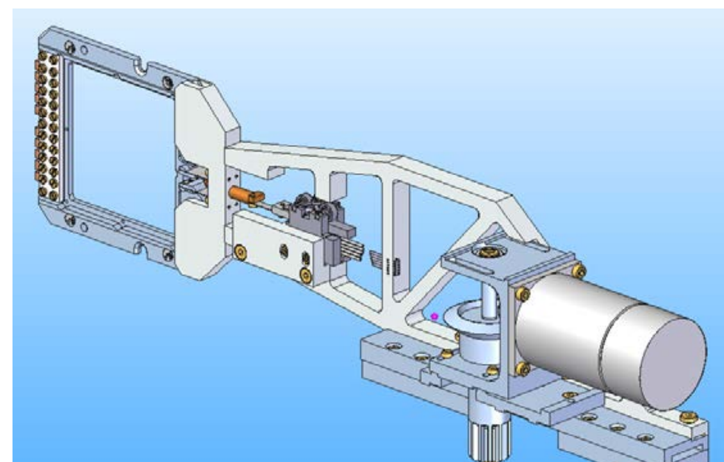


10 Hz-sample changer

- Separated mini-chamber for sample frame reservoir
  - ➔ **Keep the main chamber under vacuum**







* Current design is for SCS instrument

Design lead by C. Deiter, Sample environment group at European XFEL

Open issues

- **EMP resistance for motors**
- **Production of many number of samples**
- **Debris shield design**

The HED team *plus*

Ulf Zastrau
group leader
since Apr 2015

Th. Tschentscher
group leader
until Apr 2015

Karen Appel
(scientist)

Ian Thorpe
(engineer)

Alexander Pelka (HZDR)
(scientist)

Gerd Priebe
(optical laser scientist)

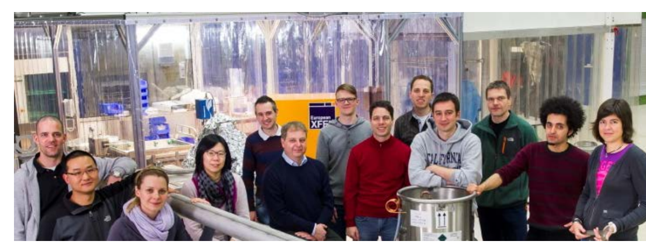
Andreas Schmidt
(engineer)

Laser group
Gerd Priebe, Guido Palmer & Max Lederer

Central Instrument Engineering team
Lewis Batchelor & Antonios Lalechos

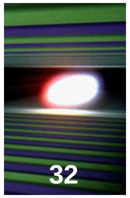
Sample environment group
Joachim Schulz & Carsten Deiter

+ Photon diagnostics, Detector, DAQ/Ctrl groups



XROBT group
Harald Sinn & Martin Dommach

Many thanks to HIBEF, advisory members and more



HIBEF User Consortium

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R. Redmer(U.Rostock), J. Wark(Oxford), E. Weckert(DESY)

Coodinator: C. Baehtz (HZDR)

HIBEF SAC/TAC
Day-1 experiment description

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M. v. Zimmermann (DESY)
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Experiment Hall, June 2013
Thank you for your attention